

Light Scattering Properties and Processes of Coastal Waters

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LONG-TERM GOALS

Characterizing the volume scattering function (VSF) of oceanic waters remains one of the most outstanding problems in optical oceanography. The goal of this project was to develop the tools necessary to significantly advance our knowledge of the VSF of oceanic waters, particularly coastal waters. This project ended early into this reporting period (FY01) and therefore there is not much new to add from the previous annual report on this project. We successfully achieved our goals, having developed the first in-situ, multi-angle profiling VSF instrument called HydroBeta. We also developed additional tools and facilities for studying ocean-optical properties and light scattering in particular, and conducted extensive ocean measurements and laboratory experiments of water optical properties.

OBJECTIVES

Our scientific objective was to measure, in situ, the volume scattering function concomitant with other optical property measurements and the particle size distribution in a wide variety of oceanic waters. Since we already have at hand a number of instruments and methods for measuring the absorption, beam attenuation, and backward-scattering coefficients [Maffione and Dana, 1997; Dana et al., 1998], the VSF measurements provided the only missing link to definitively testing instrument closure. A related objective was to investigate the accuracy of using Mie theory to compute the VSF based on the particle size distribution and index of refraction. In general we applied our VSF measurements to a wide variety of modeling problems in optical oceanography. Our technological objective was to develop accurate, in-situ profiling instruments that can measure the VSF over the range of scattering angles.

APPROACH

The existing data show that the VSF's of marine particles typically increase by four orders of magnitude as the scattering angle goes from 90 to 1 degree, and they increase by another two orders of magnitude from 1 to 0.1 degrees. This presents great difficulty in measuring the VSF, requiring exceptionally high angular resolution and dynamic range in the electro-optics of an ocean VSF meter. At larger scattering angles (approximately 30 to 170 degrees), the relative intensity of light scattered into a narrow solid angle is exceedingly small, so that highly sensitive, yet low noise photodetection is required [Maffione and Dana, 1997; Dana et al., 1998]. In addition, any in-situ VSF meter must be able to withstand the harsh ocean environment, staying radiometrically and electronically stable to maintain its calibration and accuracy. Finally, there is the important issue of accurately calibrating the

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14. ABSTRACT Characterizing the volume scattering function (VSF) of oceanic waters remains one of the most outstanding problems in optical oceanography. The goal of this project was to develop the tools necessary to significantly advance our knowledge of the VSF of oceanic waters, particularly coastal waters. This project ended early into this reporting period (FY01) and therefore there is not much new to add from the previous annual report on this project. We successfully achieved our goals, having developed the first in-situ, multi-angle profiling VSF instrument called HydroBeta. We also developed additional tools and facilities for studying ocean-optical properties and light scattering in particular, and conducted extensive ocean measurements and laboratory experiments of water optical properties.					
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instrument, which requires careful analysis of the electro-optic response of the sensor and appropriate measurements to properly characterize the light propagation through the system. Our approach to addressing this difficult instrument development project made use of the unique optical and electronic technology and calibration techniques we developed to solve the problems we faced in building instruments for measuring light scattering in the ocean [Maffione and Dana, 1997; Dana et al., 1998].

The VSF instrument we developed on this project is called HydroBeta. The opto-mechanical design of HydroBeta is unique from all previous VSF meters. Basically, a “ring” is used for mounting 12 fiber-optic light collectors that can be positioned to measure light scattering from a source beam at nearly any angle. One of the more exciting aspects of this design is that the 12 angles at which the VSF is measured can be easily changed. HydroBeta is also designed as a profiling instrument, where it measures the VSF at 12 angles simultaneously through the water column (or in time series for moored applications). The opto-mechanical design of HydroBeta is a unique and revolutionary design over all previous VSF meters. Basically, a “ring” is used for mounting 12 fiber-optic light collectors that can be positioned to measure light scattering from a source beam at nearly any angle. One of the more exciting aspects of this design is that the 12 angles at which the VSF is measured can be easily changed. HydroBeta is also designed as a profiling instrument, where it measures the VSF at 12 angles simultaneously through the water column (or in time series for moored applications).

WORK COMPLETED

The most significant achievement in new instrument was the successful development of HydroBeta, an in-situ profiling instrument designed to measure the VSF at 11 angles and the beam attenuation coefficient. A diagram of the optical layout of HydroBeta is shown in Figure 1, showing the solid ring upon which the light source and receivers are mounted. The light source and collimating optics are contained in a housing shown mounted on the “left” side of the ring in the diagram. The light source is a doubled Nd:YAG laser (532 nm) expanded to a beam diameter of 0.5 cm and collimated to 0.15 degree half-angle divergence. The beam diameter and divergence were carefully engineered and are critical to making a proper and accurate measurement of the VSF. The collimating optics include a depolarizer so that only the scalar component of the Mueller matrix, i.e. $M(1:1)$, is measured. However, the design of HydroBeta includes the provision for replacing the depolarizer with either a linear or circular polarizing filter so that other components of the Mueller matrix can be measured. Likewise, the receivers include a provision for mounting polarizing filters.

HydroBeta is unique among all ocean-optical instruments ever developed and incorporates many impressive capabilities important to gaining a more complete understanding of the VSF of ocean waters. This instrument is designed to measure the VSF at 11 angles *simultaneously* of ambient, *undisturbed* water. What’s more, these angles can be set to any 11 angles in the range from 5 to 170 degrees in five-degree increments. With a sampling rate of 1 Hz, the HydroBeta is easily used as a profiling instrument, allowing us to investigate the variability of the VSF throughout the water column concomitant with a full range of optical and physical water-property measurements.

Successfully developing a multi-angle VSF instrument is only the first, though quite difficult step in measuring the VSF of ocean waters. The next, though equally important step is the accurate calibration of the instrument. This latter step historically has been a controversial and unresolved issue, bringing into question all previously reported VSF measurements. Petzold, for example, used a purely analytical calibration technique that he himself acknowledged in his famous 1972 report contained many unresolved questions. More recent VSF makers and users of VSF instruments have

attempted to use spherical particles and Mie theory calculations of the VSF to calibrate their measurements. The problems with this approach are myriad and this approach is far from being proven or accepted. We have developed a method for calibrating HydroBeta with a method that relies only on the Lambertian properties of a diffusely reflecting target. Errors in the Lambertian target assumption are at most a few percent. The method is similar to the thoroughly documented and well tested technique we developed for calibrating the HydroScat backscattering instruments [Maffione and Dana, 1997]. This method involves measuring each receiver's response to a Lambertian target, illuminated by the instrument's light source, over the receiver's complete field-of-view. The result is a complete, absolute, in-water calibration that involves a bare minimum of assumptions, all of which can be independently verified.

RESULTS

During the development of HydroBeta over the past two years, we conducted a vigorous laboratory and field program of characterizing and modeling ocean-optical properties with an emphasis on light scattering. The results of these experiments have provided important new insights and discoveries of optical-property relationships and helped point us towards the important questions that VSF measurements can help solve. Following is a brief bullet-summary of the more salient results we have obtained on this project:

- The ratio of the backscattering coefficient to the total scattering coefficient, b_b/b , was found to vary substantially in coastal waters, suggesting that the scattering phase function also varies substantially. We found that even in a single profile, b_b/b could vary from 0.005 to 0.025. The wavelength dependence of these changes were, however, small, indicating that the VSF is only weakly dependent on wavelength.
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- A major discovery was the observation of apparent anomalous backscattering around 676 nm by phytoplankton. It was found that backscattering in this red region increased to a far greater proportion than at other wavelengths. We definitively verified that this anomalous increase was not due to contamination by fluorescence excited by the blue LED light. One possibility is that the anomalous scattering is actually caused by fluorescence excited by the red LED. More surprisingly, measurements of the total scattering coefficient, computed by $b = c - a$ from AC9 measurements, showed the reverse behavior, namely that b at 676 decreased proportionally from phytoplankton.
- In all types of coastal waters sampled, backscattering was not consistently correlated with chlorophyll concentration or chlorophyll fluorescence. Indeed in some cases there is no correlation. However, when the correlation is strong, it does tend to follow Morel's published relationship between b_b and chlorophyll.
- Our extensive measurements of spectral backscattering with the HydroScat-6 indicate that spectral backscattering better follows an exponential, rather than power law equation. Moreover,

the spectral dependence of backscattering is not constant, and depends strongly on both the nature of the particles and their size distribution.

- Measurements of spectral backscattering of the purest water we could produce in the laboratory would not produce a spectral power-law exponent larger than 3.2, substantially lower than the semi-theoretical result published by Morel in 1972. More importantly, the absolute magnitude of our VSF measurements are lower than those reported by Morel for pure water, strongly suggesting that Morel's '72 report, which has never been independently verified, could be in substantial error.
- Our laboratory scattering measurements of two commonly used scattering agents, Maalox and Formazin, revealed that these two substances have significantly different scattering phase functions. However, measurements of their particle size distributions gave nearly identical results, except for a small "hump" at around 60 microns for Maalox, probably due to coagulated particles. Subsequent Mie calculations using these two size distributions were consistent with our laboratory results, revealing that a small addition of relatively large particles can have a significant affect on the phase function. We also found that the phase function of Formazin is not consistent with the phase function of ocean waters. Considering that Formazin is the accepted standard for calibrating "turbidity" sensors, this could have substantial import to the interpretation of NTU measurements.
- We observed extensive evidence for intense microstructure in optical properties during coastal upwelling and resulting phytoplankton blooms and vertical stratification. Under certain stratified conditions these layers were observed to be modulated by internal waves. Radiative transfer calculations showed that in some cases this modulation would clearly show up as changes in the water-leaving radiance, suggesting the possibility of mapping an internal wave field from ocean-color remote-sensing imagery [Maffione, 1998].

IMPACT/APPLICATIONS

We expect that our measurements of the VSF will have an enormous impact on nearly all areas of optical oceanography. No measurements of the kind we plan to obtain have ever been made. Indeed, the nearest data of this type were obtained over 25 years ago. This lack of systematic and complete VSF measurements has greatly hampered our understanding of light scattering by marine particles, the testing and refinement of optical models, and the calibration of ocean-optical systems. Our extensive collection of optical property measurements in various coastal environments will be a critical aid in developing bio-geo-optical models of coastal waters.

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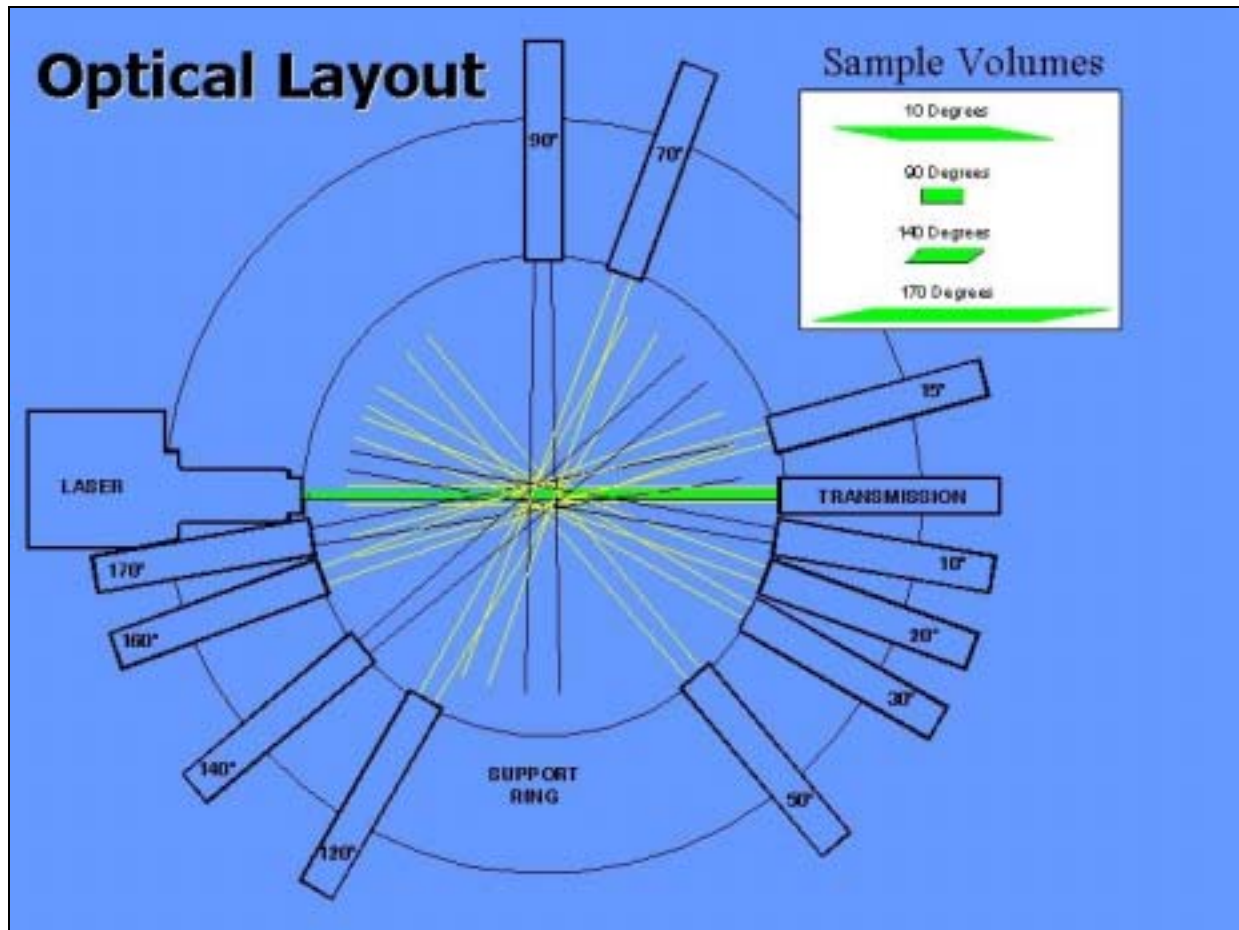


Figure 1. Optical layout of HydroBeta. The 12 receivers are mounted around the center ring. The laser and collimating optics are contained in a housing mounted on the left of the ring in the diagram. Note that the scattering volume in the center of the ring is “open,” that is, HydroBeta measures the VSF of natural, undisturbed water.